Analyzing Unusual Stars in Kepler

Research Thesis

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By

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Abstract:

The Kepler field contains two distinct groups of cool evolved stars: the red giant branch (RGB) of shell hydrogen burning stars and the red clump (RC) of core helium burning stars Typically, RC stars are hotter than RGB stars and are restricted to a narrower range of intermediate luminosities. In this project, the focus is to look at unusually hot and unusually cool RGB stars, focusing on those with luminosities below the RC. I used spectroscopic data from APOGEE and *Kepler* asteroseismology to define the bottom edge of the red clump. Hot stars below this threshold were defined as unusually hot RGB stars. I also discovered an unusually cool RGB population. I followed this up with a systematic study of these unusual stars-- first seismically, and then further spectroscopically. We then further analyze the stellar oscillations of the hot star region by looking at their power spectra, theoretical correspondence, SIMBAD information, and seismic information to explain their behavior. The results from the hot star region correspond to a truly unusual population of stars, containing binaries, rapid rotators, and other rare types of stars.

Introduction:

I am interested in studying the physics of stars and stellar populations. My tools are a large spectroscopic survey (APOGEE) and time series data from a planet-searching missions (*Kepler*). The latter can be used to study oscillations, a topic sometimes referred to as asteroseismology. Sun-like stars burn hydrogen in their core. When they exhaust core hydrogen, they become luminous red giants, which are great targets for APOGEE and *Kepler*. There is a large effort at Ohio State University to create a joint spectroscopic and asteroseismic catalog of red giant stars, and the 2^{nd} APOKASC catalog was published by Pinsonneault et al (2018). I used preliminary data from the APOKASC-3 catalog (Pinsonneault et al. 2021).

Kepler is a NASA satellite that was launched in 2009 and observed, on its primary mission, several hundred thousand objects (including red giant stars) for 4 years. My focus is on red giant stars, which are composed of two populations: the red clump (RC) and the red giant branch (RGB). Stars in the RGB phase are burning hydrogen in a shell, while RC stars are a later stage of evolution where they burn helium in the core and hydrogen in a shell. RGB stars are cooler and have a higher luminosity in comparison to the RC population. The purpose of this investigation is to find populations of red giant stars with unusual characteristics and explores the reason behind these anomalies.

I identify two distinct domains of interest: unusually hot and unusually cool stars. These stars are likely to be rare massive stars between the main sequence and the giant branch and studying them is valuable. It is also known that there are heavily spotted rapid rotators, likely to be cool stars. For RGB stars, there is a well-defined mean temperature as a function of log(g). RC stars are systematically hotter than red giant branch stars. The location of both populations depends on their composition. By comparing the temperature, surface gravity, and composition of stars to the population average I can therefore define what are “normal”, “hot”, and “cool” mean relative temperatures for red giants. Because the red clump population is so numerous, rare stars will be difficult to detect in the domain where RC stars exist. Fortunately, RC stars are only found in a restricted range of surface gravities. Therefore, we can detect rare massive hot stars below the red clump—thus I need to quantify where the bottom edge of the red clump lies.

The APOGEE survey of data is so large, that automated pipelines must be used to identify which stars lie in their respective population. These pipelines can then be checked against reference values or templates, in which can then be used to identify trends in the data that can be fitted. This is done using Apache Point Observatory Galactic Evolution Experiment (APOGEE) (Ahumada et al 2018). APOGEE measures the surface gravities, then applies a correction to put these values on a physical system. In return, there are two different spectroscopic scales; raw in which we set our scales, and then corrected. The difference between the corrected and uncorrected values is that APOGEE slightly measured the gravity higher than what the true value is, resulting in the raw data used providing above the normal subgiant branch of stars. I used the values of spectroscopic effective temperature, spectroscopic surface gravity, and asteroseismic gravity. Asteroseismic gravity is another method of measuring gravity using their internal oscillations. These seismic gravity values provide a more precise value for gravities than spectroscopic values of surface gravity.

Methods:

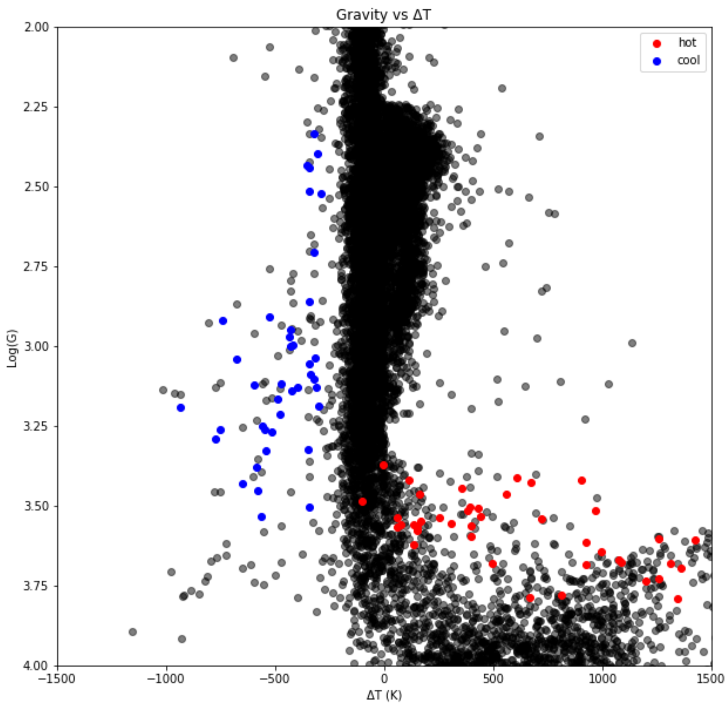


Figure 1: Log(g) as a function of ΔT; blue stars on the left correspond to cool red giants as red stars on the right correspond to hot red giants.

Stars on the red giant branch have a narrow range of temperatures and gravities, and red clump stars are hotter than that range and differ in chemical composition. APOGEE defines a reference temperature with the formula $Tref = 3032.8 + 552.6 * Log(g) - 357.1 * \left[\frac{M}{H}\right] - 488.9 * [\frac{C}{N}]$. This accounts for known trends in the data. Most stars are well described by this mean relationship, but there are clear outliers, as shown in Figure 1 to the left. This value is what is referred to as delta temperature (ΔT), or the difference between the effective temperature of a star and the reference temperature of the population. However, particularly at high surface gravity, there is clearly a population of unusual stars above and below the typical temperature values. To define the interesting population of stars, I split this into two categories: unusually hot stars and unusually cool stars, three standard deviations outside of median value of the temperature of red giant stars for this sample. Starting with the unusually hot stars, I first set out to filter out the red clump stars by defining the bottom edge, or the end of the population of the red clump. I did this by filtering out the data to only stars that are red clump and creating a histogram of the seismic gravities of red clump stars. This seismic surface gravity is obtained using

$G_{seismic} = Log\left(\left(\frac{\upsilon_{max}}{3076}\right) * \left(\sqrt{\left(\frac{Teff}{5772}\right)}\right)\right) + 4.437$ (Brown 1991). Seen in Figure 2 there is a clear, distinct bottom edge to the clump. From this, I set the constraint for the seismic surface gravity range of unusual stars to be greater than 3.0, filtering out any possible red clump stars.

The region corresponding to unusual hot stars highlighted in orange was defined by a hot temperature range (5250-6500 K) and a high surface gravity range (3.2-3.8 log(g), < 3.5 seismic log(g)) following the definition of the clump bottom limit. I then confirmed that none of our hot star candidates had the pattern of oscillations expected for RC stars. To the left in Figure 3, you can see where these stars that fall within these parameters are highlighted as orange.

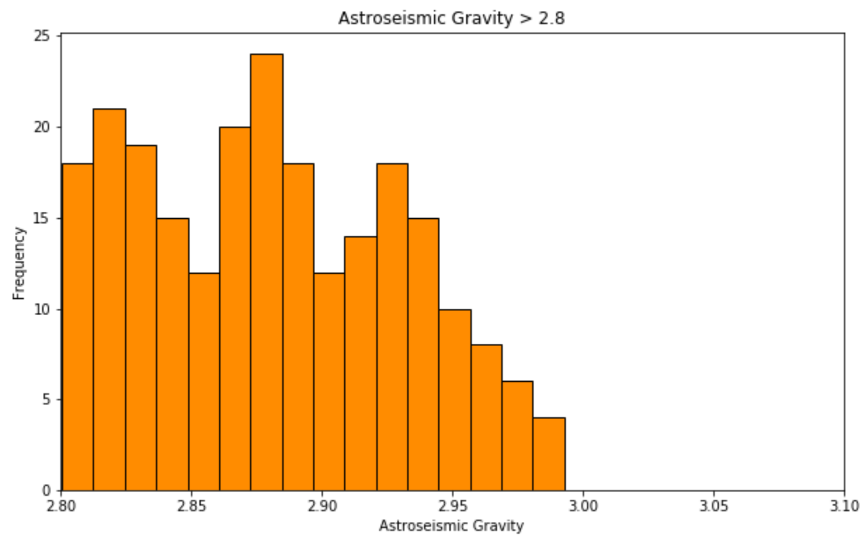


Figure 2: Histogram of Seismic Log(g) showing no stars in the red clump population of red giants showed a log(g) > 3.0

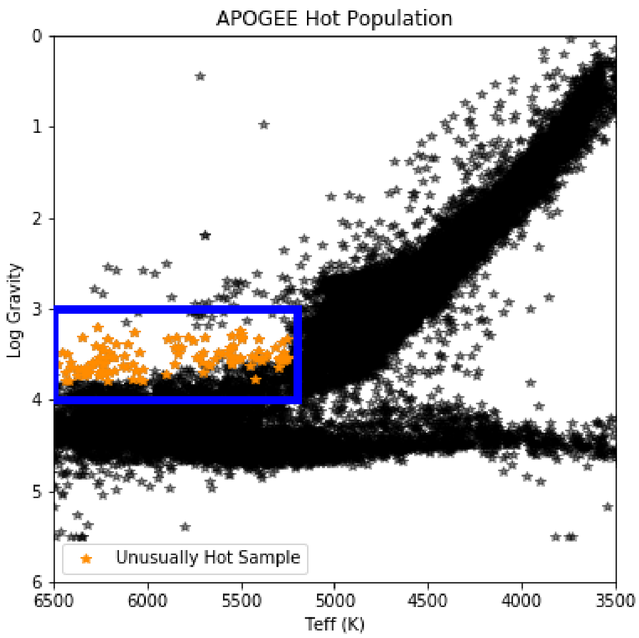


Figure 3: H-R diagram of APOGEE population with hot stars positioned in the blue boxed domain, colored in orange.

The next population is an unusually cool population of red giants. To define the constraints for this region, I looked at stars that were 3 standard deviations or greater ΔT from the RGB, and on a specific gravity range of 3.2-3.8 log(g). The stars within these constraints are shown in red on Figure 4. These stars are clearly unusual and are far too cold to be red giants. Most of the stars in my sample are much cooler than the general population, as expected. A few stars appear to be relative hot compared to the general population. This is because stars with different abundances are expected to have different temperatures and these stars are unusual relative to their chemical composition.

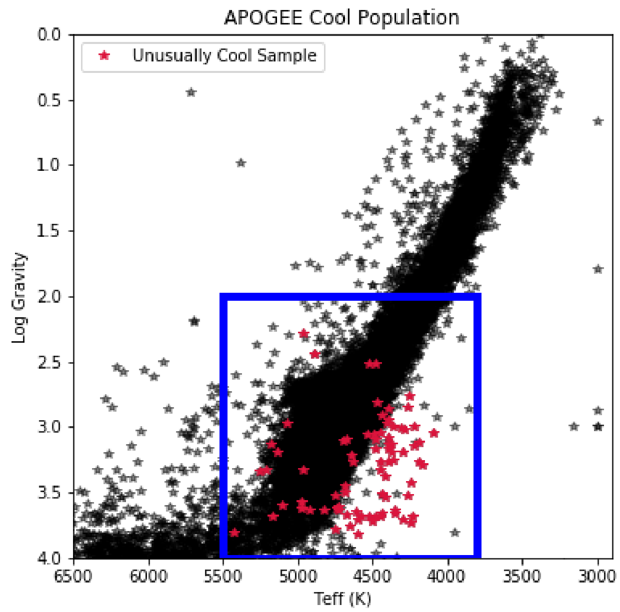
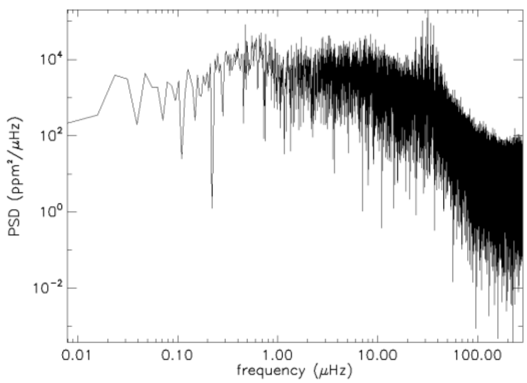


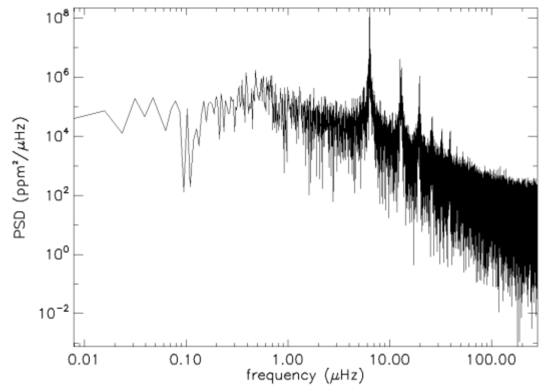
Figure 4: H-R diagram of APOGEE population with cool stars positioned in the blue boxed domain, colored in red.

Power Spectra:

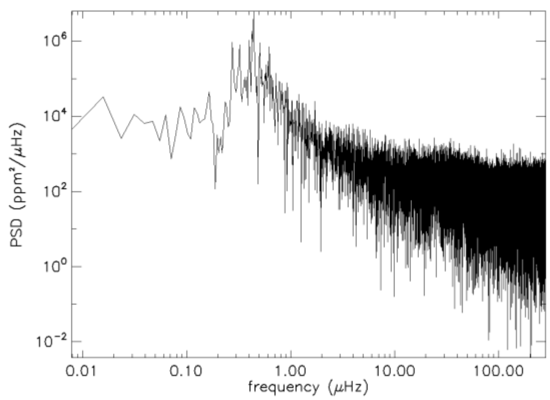
The next step is to check their seismic parameters and look at their oscillations to see if any of these stars truly are acting unusual. To do so, I obtained *Kepler* light curves, took a Fourier transform, and generated power spectra. I used the power spectra to start to categorize these anomalous stars. Many of these stars show signs of rapid rotation and solar-like oscillations. A certain number of stars with peculiar pulsations which does not correspond to solar-like oscillations were also discovered and I categorized them as weird pulsations. The number of stars that had weird pulsations is noteworthy, considering these kinds of pulsations are present in almost no normal red giant stars. Starting with the sun-like (A), of power vs frequency, this pattern displays power at specific frequencies, an excess over the background, and this is the normal thing to expect. For the rotational stars (B), the signal is usually coming from star spots and its very common to see harmonics from a single star spot. No detection cases (C) show no signed of an oscillation signal, while weird pulsation patterns (D) are not consistent with red giant oscillations and are more consistent with those of eclipsing binary stars.



A



B



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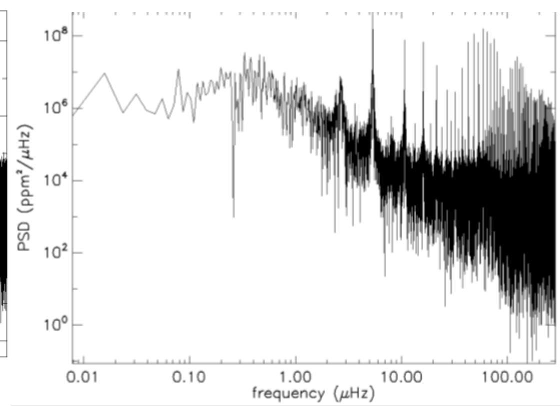


D

Figure 5: Power spectra of a sun-like pattern, rotational pattern, no detection, and weird pulsation, respectively.

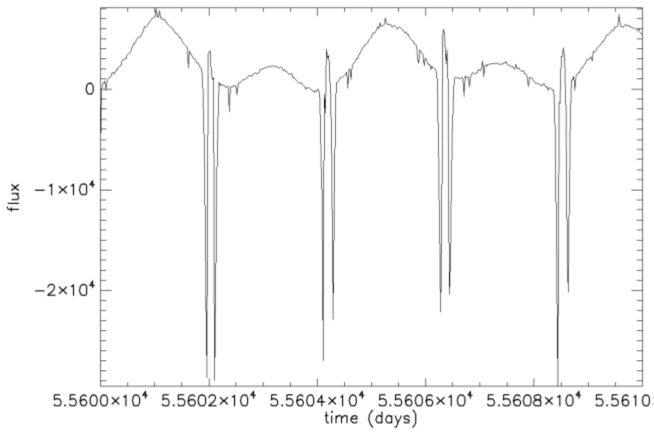


Figure 6: *Kepler* time series data for a star with a peculiar power spectrum. Eclipses are clearly visible.

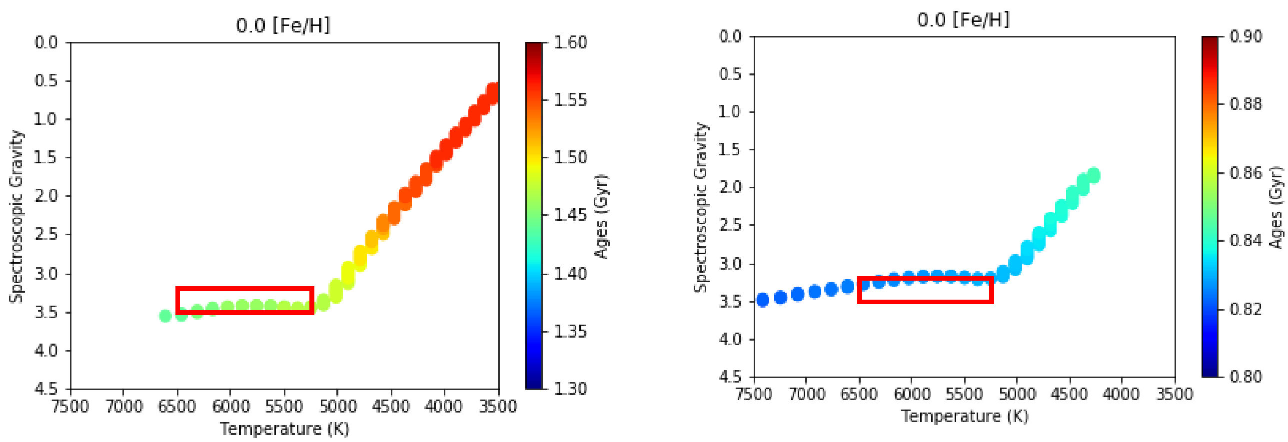
This light curve to the left corresponds to a power spectrum in the weird pulsations category above and shows the pattern that is resonant with eclipsing binaries, as one can see the double peaks in the data. The results of my study are summarized in the table below:

	No Detection	**Rotation**	**Solar-Like**	**Weird Pulsation**
Hot	28	40	8	27
Cool	68	25	15	10

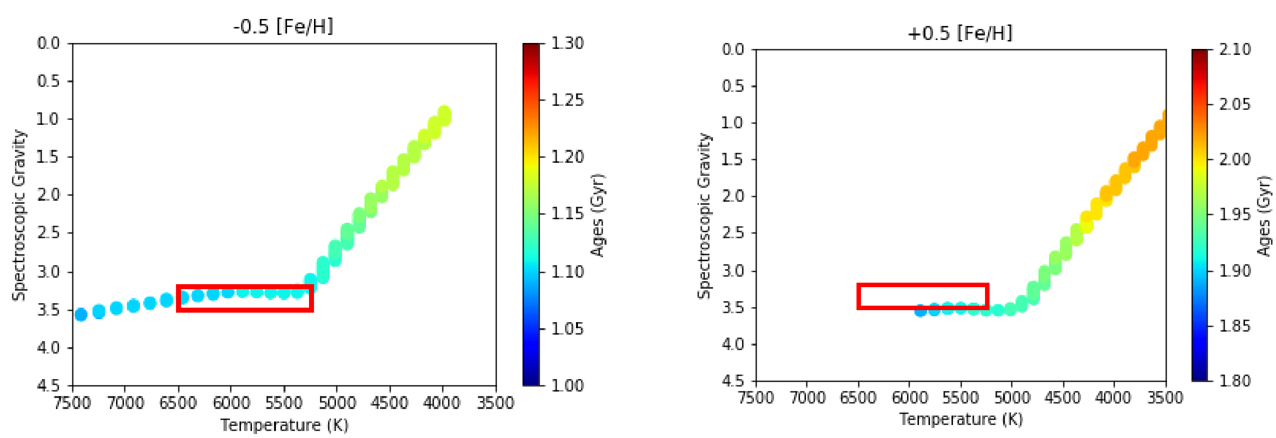
This is not a common sample for red giants. In red giants, their oscillations are detected almost every time. This is not expected for a population of stars to contain a high number of weird pulsations. It is interesting that there is a high population of rotational red giants as well. Normally, you would see mostly solar like stars, and rapid rotators represent only 1-2% of the overall population.

Theoretical Investigation:

Stellar theory predicts my hot star domain on the HR diagram should contain massive stars evolving from the main sequence. Where these stars should theoretically lie can then be compared to where the population of hot stars actually lie, to see if they correspond to the theoretical data. Using MESA Isochrones and Stellar Tracks (Dotter 2018), I selected theoretical evolutionary tracks with no stellar rotation, a mass ranges from 1.8-2.2 solar masses, and a metallicity between [Fe/H] = -0.5 to [Fe/H] = +0.5. I focused on the evolutionary state where stars are crossing from the main sequence to the RGB. I found that these stars were predicted to occupy my hot star domain. These stars are confirmed to likely be massive, chemically abundant red giants. Figures 7 and 8 correspond to an input of 1.8 and 2.2 solar masses with the same metallicity, and therefore ages, while figures 9 and 10 correspond to a mass of 1.8 solar masses differing in metallicity, revealing chemical abundances.



Figures 7 & 8: H-R diagram of theoretical MIST package data with mass 1.8Msun and 2.2 Msun respectively at the same metallicity. The red box here indicates where my real hot population lies, confirming theoretical values of mass 1.8-2.2 Msun for my hot star population.



Figures 9 & 10: H-R diagram of theoretical MIST package data with mass 1.8 Msun and a changing metallicity of -0.5 and +0.5. The red box here indicates where my real hot population lies, revealing theoretical values for chemical abundances for my hot star population.

Categorization:

After observing where these stars lie theoretically and categorizing their power spectra, I then went to conduct a simple SIMBAD search of the unusual hot population to discover what information is known of them. From this we will then be able to deduce stars that are simply interesting and focus on the stars are truly unusual red giants. I obtained the following list of stars that had been flagged as being unusual in prior published papers:

Eclipsing Binaries	Rotationally Variable Star	Ellipsoidal Variable Star	Eruptive Variable Star
21	29	1	5
Variable Star of Delta Sct Type	Variable Star of Gamma Dor Type	Star	Not found in Database
6	3	35	14

The last stars were particularly interesting because it means they have peculiar parameters without obvious reasons. Therefore, these is something to be unveiled here. Interacting binary stars can be found in unusual places and a number of these categories (ellipsoidal etc.) fall into this class. Others (delta sct, gamma dor) correspond to detected oscillations of stars that are not red giants. However, we also found a number of stars that had not been flagged as unusual.

Seismic Investigation:

The goal of the seismic investigation is to look at the asteroseimisc values of $\Delta\upsilon$ and check its correspondence to υ_{max} using power spectra. $\Delta\upsilon$ corresponds to the large frequency separation between consecutive radial modes of the same angular degree l while the υ_{max} value corresponds to the frequency maximum of the power spectrum. $\Delta\upsilon$ is related to the global density of the star, therefore the surface gravity. A seismic check can be done by creating a synthetic spectrum of the oscillation (Mosser et al 2011) to compare if the $\Delta\upsilon$ value was well determined.

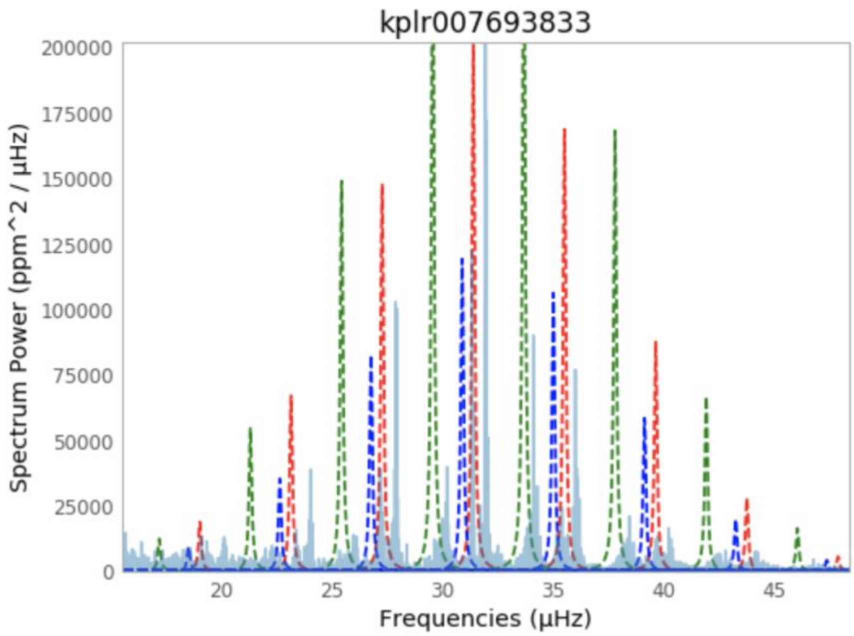


Figure 11: Synthetic spectra plotted over the real spectra of star KIC007693833. Red modes are angular degree l=0, green modes are l=1, and blue modes are l=2.

To construct the synthetic spectrum, a Lorentzian that represents each oscillation mode was created. The characteristics of the oscillations are described by the spherical harmonics (n,l,m) where n describes the number of radial nodes of the wave we are considering and l is the number of nodes on the stellar surface. Mode frequencies correspond to the oscillation frequencies the star follows according to its physical properties. The modes with the highest amplitudes will be the ones with angular degree l=0, l=1, l=2. Therefore, we will focus on these modes to construct the spectrum. The mode frequencies were constructed with the universal pattern from equation 3 Mosser et al. 2011, the width of the Lorentzian were determined following Belkacem et al. (2012). The width of the envelope of the spectra was obtained with $n_{env} = \delta\upsilon_{env}/\Delta\upsilon$. This was then fitted as a gaussian envelope at maximum oscillation signal to construct a spectra-like pattern. This check of seismic parameters appeared to show that these values of $\Delta\upsilon$ and υ_{max} were corresponding to the initial measured values. In figure 11 above, the synthetic spectrum in the colors of red, green, and dark blue, correspond to mode frequencies of 0, 1, and 2 respectively. There is still work to be done here—there still needs to be a fine tuning of the parameters to measure a greater precision of $\Delta\upsilon$ and mixed mode frequency pattern.

Conclusion:

My results confirm that indeed I did identify an unusual population of red giant stars, and that their unusual spectroscopic properties were not just errors in *Kepler* data. First, I used mean temperature values of the red giant branch to define what it is to be "cool" and "hot". I then defined a bottom edge to the red clump to filter out any red clump stars and reveal hot, massive red giant branch stars. Then these unusually hot and cool stars power spectra were observed to categorize these stars into no detection, rotational, solar-like, and weird pulsation stars. Focusing on the hot population further, theoretical values were obtained to see where the mass values correspond to the 'box' on an HR diagram to the expected masses of stars with the temperatures and gravities in my hot star domain. It was found that theoretically, these stars are massive, chemically abundant stars. I then investigated what was already known about the hot star sample. A literature search uncovered a large number of binary, variable, or otherwise peculiar stars. In some cases, we could obtain asteroseismic data. For these stars, I confirmed by visual inspection that the catalog frequency of maximum power and frequency spacing values were correct. I did find a few stars that were interesting stars that may not be considered to be unusual, such as the various variable stars. It might be an explanation for the peculiarities of their characteristics, but that is not proven yet. The truly unusual populations of stars I found were rapid rotators and different classes of interacting binary stars.

In summary, the population of unusual hot stars that I found are a mixture of interacting binary stars and massive stars leaving the main sequence and on their way to the red giant branch. A large majority of the cool stars are active rapid rotators. Both groups are astrophysically interesting and worthy of follow-up study.

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